Initial Dilution Zone and Limited Use Zone Concepts for Receiving Streams

Alberta
ENVIRONMENT

INITIAL DILUTION ZONE AND LIMITED USE ZONE CONCEPTS FOR RECEIVING STREAMS

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1.0 INTRODUCTION

This report describes methods of analysis, benefits, limitations, and criteria associated with implementing an Initial Dilution Zone (IDZ) for reducing possible impacts of effluents discharged to Alberta streams and identifies effluent discharge methods capable of producing an IDZ. An example (a pulp mill effluent discharging to the Athabasca River) is presented to illustrate the use of an IDZ.

This report is an extension to the Technical Manual on Procedures and Methods for Evaluating Water Quality Changes in Receiving Streams. The Technical Manual described the various components of the mixing zone (e.g. the Limited Use Zone and the Zone of Passage). These zones are associated with a condition where an effluent is discharged continuously from a bank outfall with velocities less than stream velocity (i.e. a passive plume discharge). Under these conditions, the configuration of the zones can only be altered by changing the concentration of the particular effluent parameter or by differences in the flow rate of the receiving stream.

In some situations, in order to avoid an impact on a downstream water user, it may be necessary to change the configuration of the zones without altering the effluent quality or relying on certain stream flow rates. This requires a high degree of dilution at the source of effluent discharge that can only be accomplished by using discharge methods other than a passive plume outfall. Investigating alternate methods of effluent discharge is considered a Level III (Special Studies) analysis. The need for such a study can be identified in Level I or Level II analysis, as outlined in the Booklet for Industrial Projects under the Clean Water Act.

1.1 OBJECTIVES

The overall objective is to describe the use of an IDZ for reducing the possible impact of an effluent discharged to a receiving stream. More specifically, the objectives are as follows:

1. Describe methods and procedures of discharging an effluent to a receiving stream that are capable of producing an IDZ.
2. Develop a method of analysis for delineating an IDZ and show the relationship between the IDZ and the Limited Use Zone (LUZ) in predicting water quality changes in receiving streams.
3. Describe the benefits, limitations and criteria for using an IDZ when assessing a receiving stream.

1.2 METHODS AND PROCEDURES

At the outset, historical information on IDZ was collected. Almost all of the information was obtained from British Columbia Ministry of Environment and from research conducted by Dr. N. Rajaratnam at the University of Alberta.

Although the mathematical equations for IDZ mixing analysis are provided, the equations and procedures are simplified for practical applications by providing a simple micro computer model capable of predicting water quality changes. An example, using the Athabasca River as a receiving stream for effluent discharge from a chemi-thermomechanical pulp mill (CTMP) is used to illustrate mixing characteristics associated with an IDZ and shows relationships between the IDZ and the LUZ. Moreover, the example reveals, at least in part, the criteria and importance of selecting appropriate effluent discharge methods to reduce possible impact on water users.

The hydrologic and hydraulic data on the Athabasca River at Windfall Alberta, used in this study, are identical to those used in the Technical Manual, in order to compare the mixing characteristics and mixing zones associated with each of the methods used for effluent discharge.

2.0 EFFLUENT CHARACTERISTICS

In general, pulp and paper mill effluent characteristics are a reflection of the mill process and operation, and raw materials (chemical additives, wood species). Effluent quality differs widely even between mills of the same generic classification (i.e. kraft, sulphite, CTMP, etc.). As compared to the kraft mill, the CTMP effluent is more toxic, mainly because kraft mills recover and incinerate over 90% of their process liquor and the CTMP mills have a lower water requirement and practise extensive water recycle leading to a concentration of materials (Mackenzie and Marsh 1986 and McCubbin 1983). The main constituents of the CTMP effluent which are important to water quality in a receiving stream are: bio-chemical oxygen demand (BOD_5), total suspended solids, pH, colour, dissolved oxygen, foam and scum, temperature, chemicals used in pulping and bleaching, dissolved organics (resin acids, fatty acids, alcohols, and phenols), and toxicity.

Resin and fatty acids in pulp and paper effluent are the principle substances responsible for toxicity to aquatic life (Cherwinsky and Murray 1986). In a study of nine pulp mills in Ontario, the authors found that resin acids frequently exceeded the 96 hr LC_{50} toxic levels. In particular, abietic acid, was detected at concentrations 14 times greater than the 96 hr LC_{50} limit (1.1 mg/L) for rainbow trout in 10 out of 25 final effluents tested. It is unknown whether the high concentrations were associated with a particular type of mill, process or raw material. It is possible however, that such concentrations can be produced by CTMP mills. Mackenzie and Marsh (1986) reported concentrations as high as 42 mg/L of total resin acids in CTMP mills.

Because abietic acid is an important and conservative parameter, it is used to illustrate the example of mixing and predicting water quality changes in a receiving stream. The assumed effluent variables are as follows:

Effluent flow - 0.145 m^3/s (based on 25 $m^3/t/d$ of product and a mill capacity of 500 t/d),

Parameter to be tested - abietic acid,

Concentration of abietic acid in the effluent - 8.0 mg/L (one-half the maximum concentration reported in the Ontario study of 15.8 mg/L is selected to represent the median effluent concentration),

Acute toxicity concentration of abietic acid - 1.1 mg/L,

Background concentrations in the receiving stream of abietic acid - 0.0 mg/L, and

Receiving stream water quality guideline for abietic acid - 0.04 mg/L (detection limit reported in the Ontario study).

3.0 STREAM CHARACTERISTICS

The stream data needed to assess mixing in receiving streams and their methods of derivation have been discussed in Section 2.2.2 of the Technical Manual (A.A. Aquatic Research Limited 1986). The relevant data from that study are summarized below:

3.1 HYDROLOGIC CHARACTERISTICS

The 1 in 10 year return period seven day low flow event (7Q10) for various times of the year when the environmental conditions in the receiving stream could be considered critical are as follows:

a) Ice cover - winter (March) 32 m^3/s
b) Open water - fall (October) 110 m^3/s
c) Open water - summer (August) 270 m^3/s

For comparison, the mean annual flow rate of the Athabasca River at Windfall is about 253 m^3/s.

3.2 HYDRAULIC CHARACTERISTICS

In assessing the receiving stream associated with a passive plume discharge, average values for the hydraulic characteristics (surface width, average depth and average velocity) are used, as shown in the Technical Manual. Relationships between these characteristics and flow rate can be developed from either general information contained in Kellerhals et al. (1972) or field data from a number of detailed flow measurements at the outfall site (or a nearby Water Survey of Canada Station).

In the Technical Manual the use of the MIXAPPLN computer model to predict water quality changes in the stream was described. The procedures can be applied to rivers where the reach of interest has a relatively prismatic cross-section (i.e. non varying in shape at successive sections).

If the use of a jet for discharging an effluent is anticipated, then knowledge of the exact hydraulic conditions at the point of discharge is required for assessing the receiving stream. At least one detailed hydrometric field survey would be required to obtain the hydraulic data.

Using the same river site as that described in the Technical Manual, at which a detailed cross-section is available, the three critical flow conditions are outlined (Figures 1, 2 and 3). In these cross-sections, a deep and relatively uniform portion of the river exists near the right bank. This region is most suitable for discharging an effluent from a jet. The hydraulic conditions for this region during the critical flow conditions are presented in Table 1.

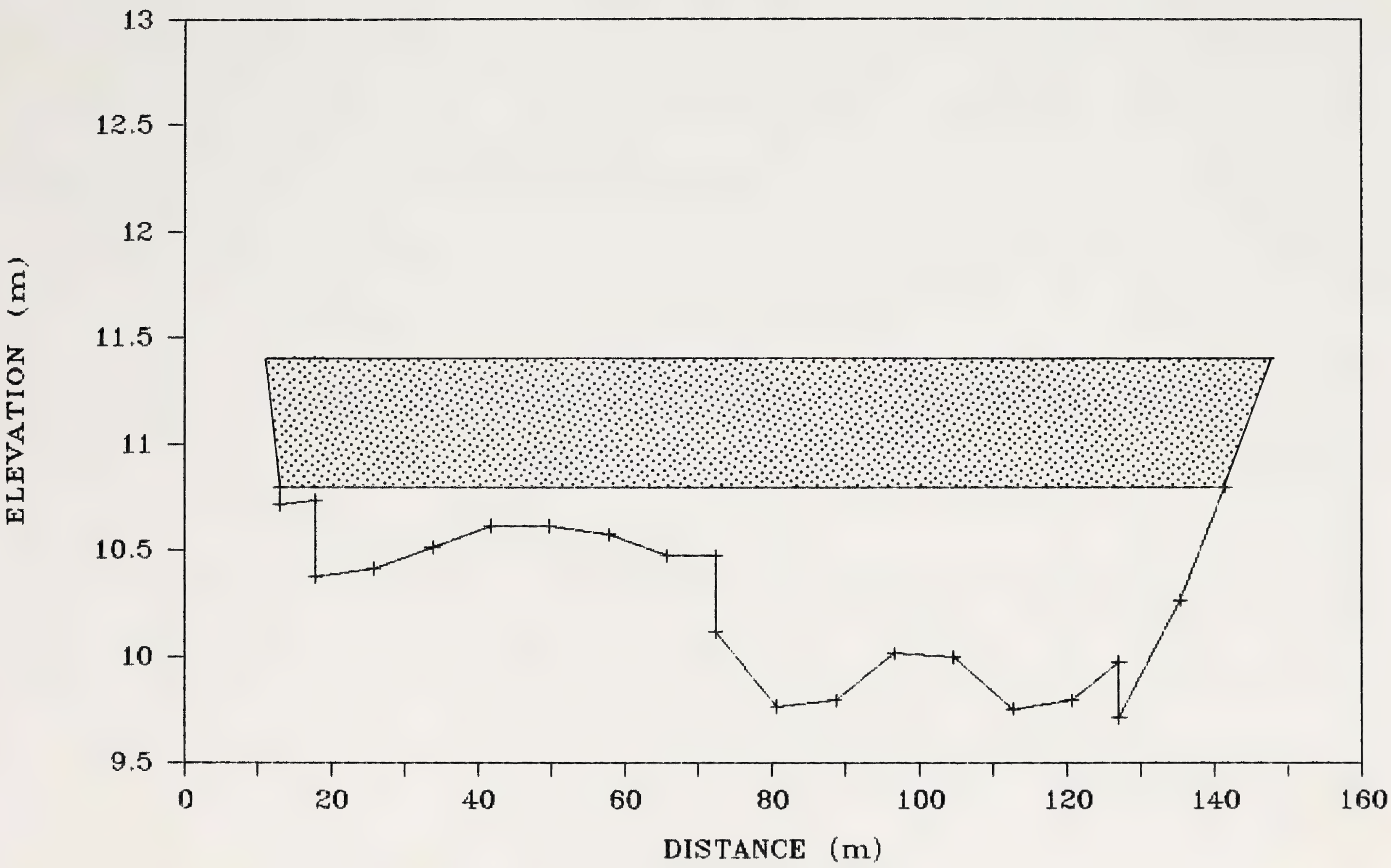

Figure 1. Ice cover conditions - 32 m^3/s.

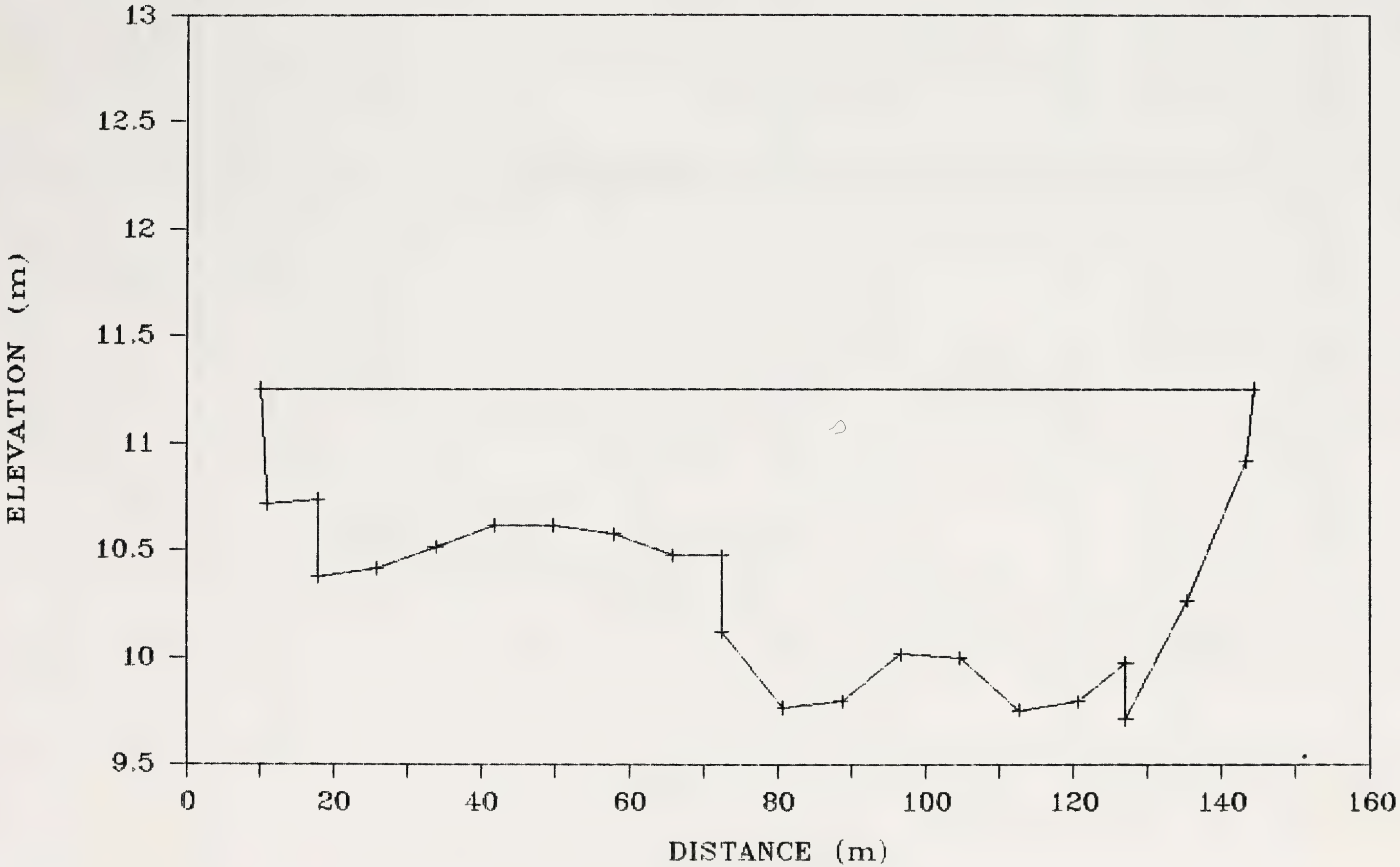

Figure 2. Open water flow - 110 m^3/s.

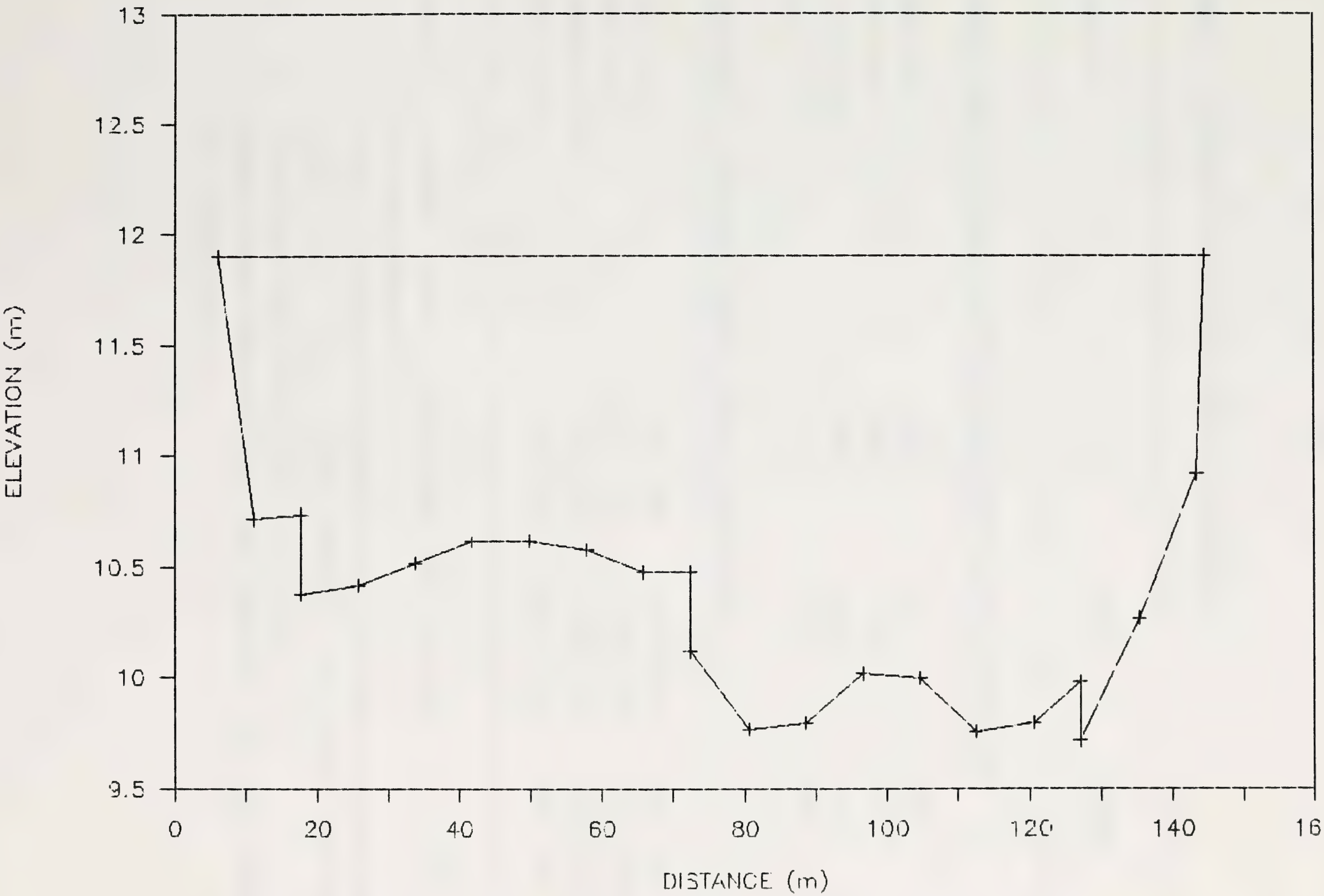

Figure 3. Open water flow - 270 m^3/s.

Table 1. Hydraulic conditions at point of discharge.

Condition	Winter	Fall	Summer
Cross-Section Averaged Conditions (for Passive Plume discharges):			
Width (m)	129	133	138
Depth (m)	0.56	0.91	1.53
Velocity (m/s)	0.44	0.91	1.28
Flow (m^3/s)	32	110	270
Conditions in Discharge Region (for Jet Discharges):			
Width (m)	50.7 (39)	50.7 (38)	50.7 (37)
Depth (m)	0.95 (170)	1.38 (152)	2.04 (133)
Velocity (m/s)	0.52 (118)	0.98 (108)	1.38 (108)
Flow (m^3/s)	25.0 (78)	68.6 (62)	143 (53)

Notes:
1. Numbers shown in parentheses are percentage of the cross-sectional average.
2. Discharge Region is the portion of the river near the right bank (from station 76 m to Station 127 m). The effluent would be discharged over some portion of this width.
3. Passive Plume discharges are those associated with bank outfalls or line diffusers.

4.0 EFFLUENT DISCHARGE METHODS AND MIXING

4.1 GENERAL

Bank discharges for an effluent are generally the most economical of the outfall configurations. The outfall line usually extends sufficiently into the river so that the discharge is submerged during the lowest critical 7Q10 flow (submergence is a means to lessen the likelihood of foaming and aid in initial mixing of warmwater discharges). Depending on the channel cross-section and the outfall location, the mixing of an effluent from a bank discharge can be analyzed using the MIXAPPLN computer model. The model predicts the concentrations of the water quality parameters downstream of the effluent discharge and delineates the Limited Use Zone (LUZ) and Zone of Passage (ZOP) components of the mixing zone.

The length of the LUZ may be considered too long if it encroaches on aquatic habitat or an existing or potential water user. In such a case, the allowable effluent concentration may require adjusting to ensure that water quality guidelines are met at these sites. Changing the treatment process is likely an expensive proposition, therefore it may be prudent for a proponent to first evaluate alternative outfall configurations prior to reassessing the treatment facilities. An alternative outfall configuration might allow the proponent to satisfy a stringent set of LUZ constraints. Alternative outfall configurations are described in the following sections (analytical methods for evaluating these configurations are presented in Section 5).

4.2 RELOCATION OF POINT SOURCE PASSIVE PLUME OUTFALL

Although a point source passive plume outfall can be located at any point across the width of a river, the bank discharge point source passive plume outfall (discussed in the Technical Manual and analyzed by the MIXAPPLN model) is the simplest and most common form of effluent discharge. However, in some instances, it may be desirable to prevent high concentrations from occurring along the near shoreline. In such cases, locating the discharge point near the middle or near the far side of the river may be more appropriate.

One advantage of a mid-stream effluent discharge is that the mixing length is significantly reduced because the plume is free to expand laterally towards each bank. This reduces the mixing zone length to 1/4 that for a bank discharge.

4.3 LINE SOURCE PASSIVE PLUME OUTFALL

A line source passive plume outfall is one that extends across a substantial portion (i.e. 10% or more, in terms of river flow) of the width of the river. The typical configuration for a line source passive plume outfall involves an outfall line buried in the river bed and extending from one bank (Figure 4). From the high water level to the winter 7Q10 water level, the pipe is buried to prevent scour. From this point on, the pipe crown is at the level of the river bed and has holes which allow the effluent to be discharged to the river. The outlets are sized to allow the effluent to be discharged at velocities that are in the order of the river velocity (i.e. about 1 m/s). Typically, the distance to which a line source outfall can extend is limited to being slightly less than the LUZ width constraint.

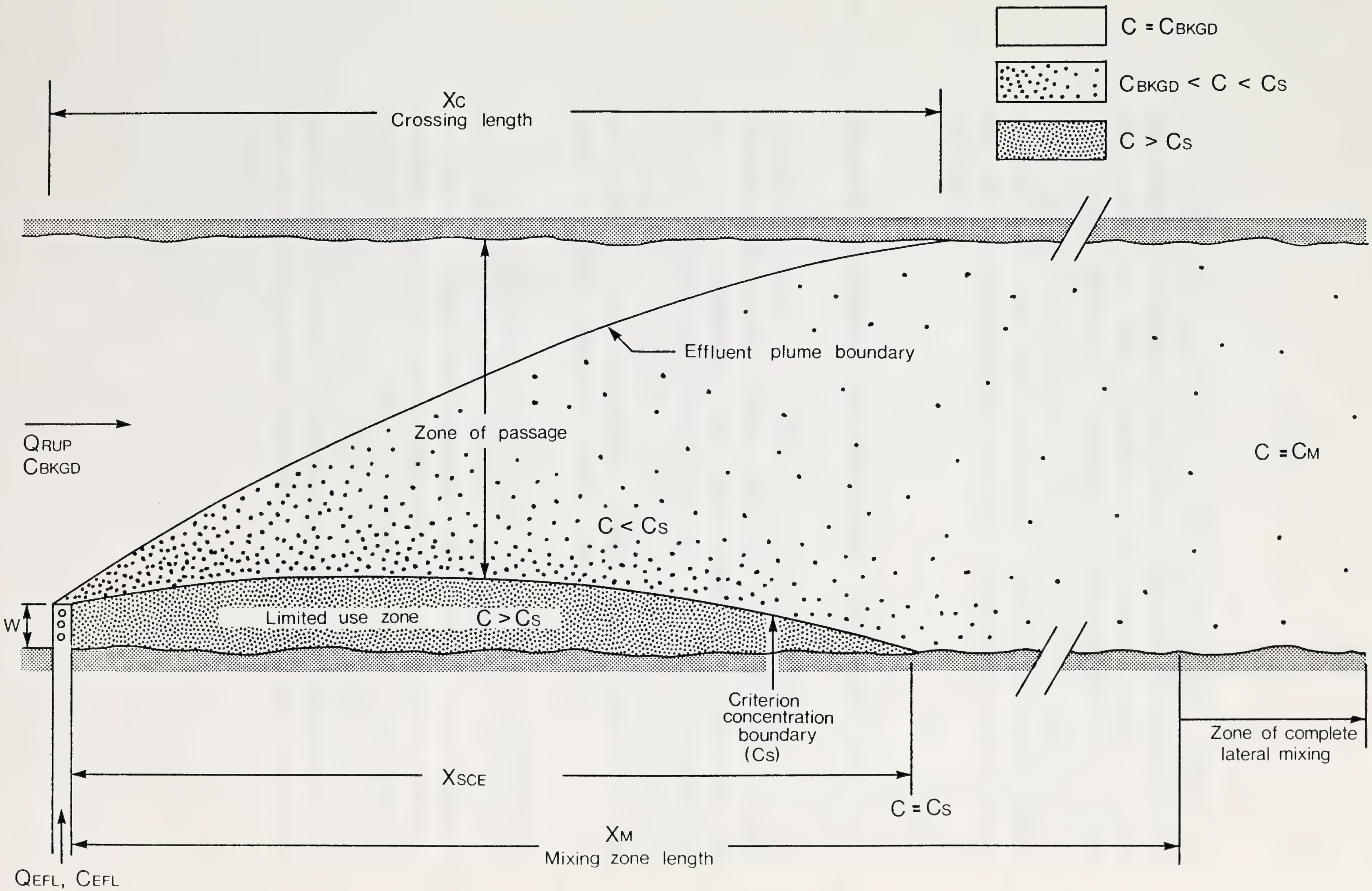

Figure 4. Mixing zone characteristics - line source plumes.

In the line and point source outfall configurations mixing is facilitated by turbulence of the river. The main advantage of the line source is that, although the mixing length is not substantially decreased as compared to a bank outfall (e.g. a line source extending to midstream has a mixing zone length that is about 7/8 that for a bank discharge), the effluent concentrations along the shoreline decrease much more rapidly (i.e. the LUZ can be shorter).

4.4 CREATING AN INITIAL DILUTION ZONE (IDZ) USING JETS

If adequate mixing of an effluent in a receiving stream cannot be established with passive plume discharges (i.e. the extent of the LUZ is not satisfactory), an Initial Dilution Zone (IDZ) can be created to substantially shorten the LUZ. The IDZ is considered a sub-component of the LUZ. The IDZ is established by one or more high velocity jets discharging effluent perpendicularly to the flow of the river (these are termed "crossflow jets").

In the IDZ, the mixing phenomenon is dominated by the turbulence of the high velocity jet discharge rather than the turbulence of the river. After some distance downstream of the discharge (usually about 25 times the diameter of the jet), the jet velocity diminishes to that of the river velocity. Within this distance, extensive mixing occurs (dilution can be in excess of 20:1). Downstream of the IDZ, the mixing phenomenon is dominated by the river turbulence as that described for the point and line source outfalls.

Two types of crossflow jets that can be considered (Figure 5). The first is a side discharge, where the jet is discharged laterally across the river from the streambank or a bridge pier. The jet is located at about mid-depth for the lowest critical 7Q10 flow condition. The extent of mixing for this configuration is controlled by the ratio of the jet velocity to the river velocity (R = Uo/U). The degree of mixing is related to this velocity ratio; although there are constraints on the maximum jet velocity (discussed in Section 5) which limits R to values between 3 and 10 for most rivers. Other constraints relate to the depth of the river. There must be sufficient depth to allow the jet to expand. This form of IDZ requires a very deep river section to be effective.

Second is a bottom discharge type which is similar to the line source outfall discussed in Section 4.3, except for the discharge structure itself. The outfall line is buried to the point where the river is relatively deep. The effluent is then discharged through several nozzles that are designed to generate high velocity jets discharging vertically from the bottom of the river. These jet streams are bent by the river flow resulting in extensive mixing occurring in a short distance.

Bottom discharge jets have a maximum jet velocity constraint that is depth dependant. As well, they have a diameter constraint that is depth dependent (usually, the jet diameter is in the order of 50 mm to 150 mm). Because the jet diameter is small, there is usually a need for several jets to discharge the effluent. With several jets, adequate spacing along the outfall structure is required to prevent their interference. Simple equations to determine all of the above relationships are presented in Section 5.

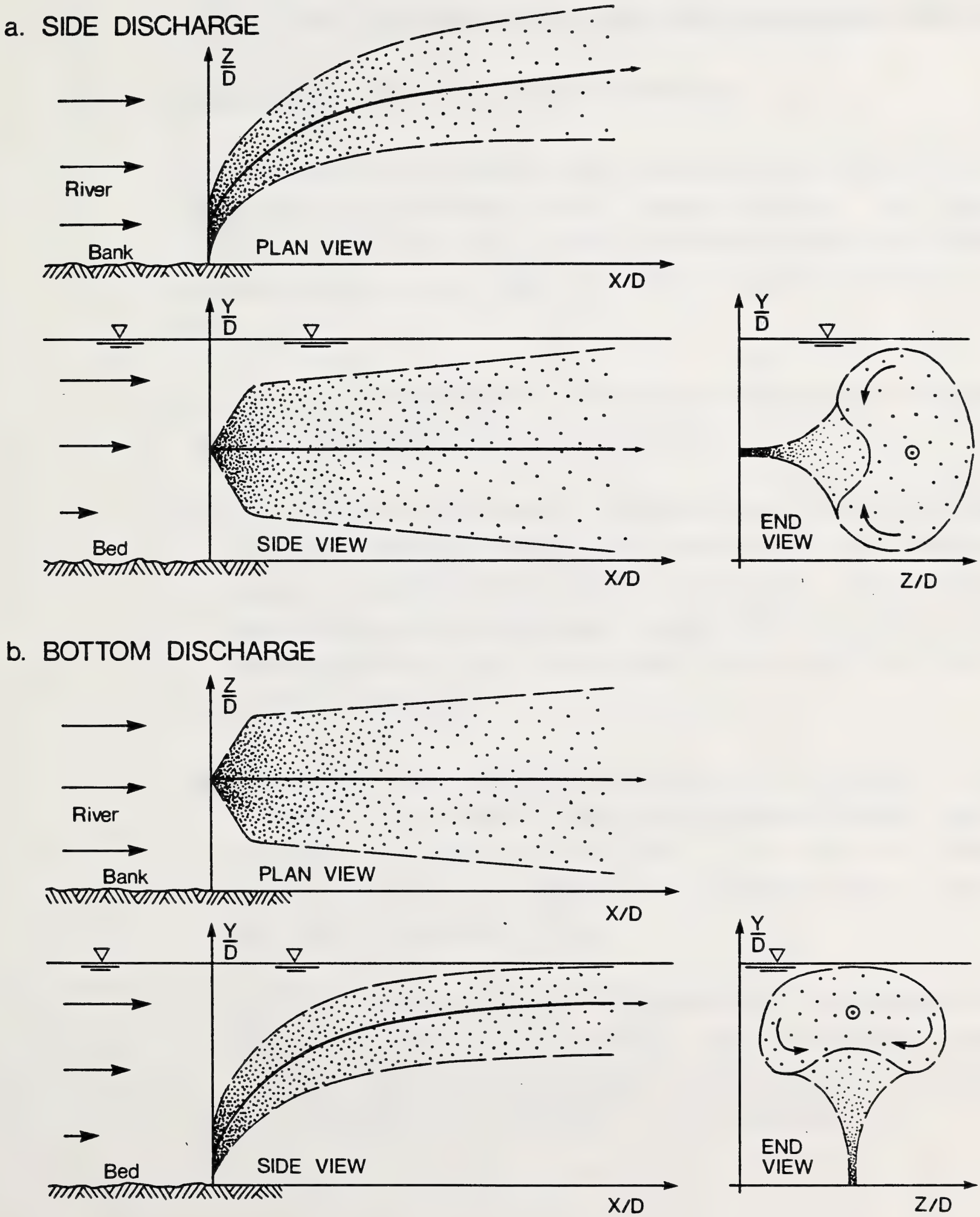

Figure 5. Typical jet discharge configurations for rivers.

5.0 ANALYTICAL PROCEDURES FOR EFFLUENT DISCHARGE METHODS

5.1 RELOCATION OF POINT SOURCE OUTFALLS

The analysis for the passive plume discharge of an effluent from a bank outfall was presented in the Technical Manual. This mixing phenomenon was analyzed by the MIXAPPLN model. The model provided concentrations at points within the mixing zone and delineated the LUZ.

In order to use MIXAPPLN for point source outfalls other than bank outfalls, the following must be considered:

a) QCP on line 10 of the file structure (see Table 12 in the Technical Manual) describes the location of the outfall (in terms of cumulative flow) from the near bank. QCP = 0 for a bank outfall; for a midstream outfall, QCP is one half of the streamflow rate plus the effluent's flow rate (i.e. QCP = (QRUP + QEFL)/2).

b) Although several streamflow conditions can be analyzed in one pass for a bank outfall, only one streamflow condition can be assessed at a time (i.e. use MQ = 1 on line 5). Several effluent flow rate and temperature conditions (lines 6 and 7) can still be assessed at once.

c) Any LUZ information must be determined by examining the computed stream concentrations; the information under "Critical Point Method Results" (see Appendix B in the Technical Manual) is relevant to bank discharges only.

5.2 LINE SOURCE OUTFALLS

5.2.1 Concentration Equation

The effluent concentration at any point downstream of a line source passive plume discharge is determined by using the following explicit (can be solved with direct use of variables) analytical equation:

$$C\ (\emptyset,p) = R \cdot CB$$

$$+ \frac{R \cdot CA}{2 \cdot w} \sum_{n=-\infty}^{n=+\infty} \left[\operatorname{erf} \left\{ \frac{(2n+w-p)}{\sqrt{2X/X_m}} \right\} + \operatorname{erf} \left\{ \frac{(2n+w+p)}{\sqrt{2X/Xm}} \right\} \right] \quad (1)$$

Where:

C (Ø,p) is the concentration at a location (Ø,p) downstream of the outfall,

Ø is the dimensionless distance downstream of the outfall [$\emptyset = (Ez \cdot X) / (B^2 \cdot U)$],

p is the dimensionless location of the point in the cross-section (note: this and other lateral locations are expressed in cumulative relative discharge; i.e. q/QR),

R is the decay factor [$R = \exp(-K \cdot X/U)$],

K is the decay rate coefficient (1/second),

X is the longitudinal distance downstream (m),

U is the average stream velocity (m/s),

CB is the background concentration upstream of the outfall (mg/L),

CA is the increase in the mixed concentration due to the effluent [$CA = (CEFL \cdot QE) / (QR+QE)$],

CEFL is the effluent concentration (mg/L),

QE is the effluent discharge rate (m^3/s),

QR is the streamflow rate (m^3/s),

Ez is the transverse mixing coefficient (m^2/s),

B is the width of the stream (m),

n is the image number,

w is the dimensionless width of the outfall (i.e. it extends from p=0.0 to p=w),

Xm is the bank outfall mixing length [$Xm = (B^2 \cdot U) / (2 \cdot Ez)$].

This formulation was developed in Hodgson (1986) from more complicated expressions presented in the literature by Yotsukura and Cobb (1972) and Lau and Krishnappan (1981). The validity of the equation was confirmed by comparison with field tests in all three papers. In using the above formulation to predict concentrations downstream from a line source outfall in a receiving stream, a number of factors should be considered:

a) concentrations can be in mg/L or any consistently used units,

b) the reference bank for q, p and w must be consistently used (in this report, p=0 is the right bank),

c) the number of terms that must be evaluated is small (i.e. use the equation for n= -2, -1, 0, 1 and 2),

d) as the error function (erf) does not appear on most scientific calculators, values are tabulated in Appendix A.

The manual application of this equation is not necessary for the evaluation of an effluent discharge. As the calculations are quite tedius, computer programs have been developed to predict effluent concentrations. Programs such as RIVMIX reported in Krishnappan and Lau (1982) can be used.

5.2.2 LUZ Boundary Equations

In evaluating the LUZ for an effluent discharge the first consideration is to evaluate the conditions at the critical point. The critical point is the point on the LUZ boundary (i.e. where p=pl) where the effluent concentration is at a maximum. This is found by examining the simulated stream concentrations if a computer program is used. Alternatively, the critical point conditions can be determined by using special equations. In this report special equations are used to show differences between point source and line source outfalls.

Gowda (1980, 1984) developed simple expressions for the concentration at the critical point (CL) and the distance to this point (XL) for a point source bank outfall:

$$CL = CA \, / \, (2.066 \cdot pl) \tag{2}$$

$$XL = \frac{(pl \cdot B)^2 \cdot U}{2 \cdot Ez} \tag{3}$$

Hodgson (1986) developed similar expressions to define the critical point conditions for line source outfalls:

$$CL = \frac{CA}{2w} \left[erf\left\{ \frac{(pl+w) \; [\ln \, (pl+w) - \ln(pl-w)]}{2 \sqrt{pl \cdot w}} \right\} - erf\left\{ \frac{(pl-w) \; [\ln(pl+w) - \ln(pl-w)]}{2 \sqrt{pl \cdot w}} \right\} \right] \tag{4}$$

$$XL = \frac{pl \cdot w \cdot B^2 \cdot U}{Ez \, [\ln(pl+w) - \ln(pl-w)]} \tag{5}$$

The concentration at the critical point should be less than the instream water quality guideline (CS). If it is not, then changes in the outfall configuration (e.g. the width of a line source outfall) or the concentration contribution by the effluent (CA) must be made and the equations applied again.

The second consideration for the LUZ is to determine its downstream extent (Xsce). Hodgson (1986) developed an equation for the downstream extent of the LUZ for a point source bank outfall:

$$Xsce = \left(\frac{CA}{CS}\right)^2 \frac{B^2 \cdot U}{\pi \cdot Ez} \qquad (6)$$

There is no explicit equation available for determining Xsce for a line source outfall. However, Xsce can be determined by an iterative process using equation (1). Xsce is the value of X, defined in equation (1), which balances both sides of the equation when C(∅,p) equals CS. Typically, Xsce for a line source is less than that for a point source outfall.

5.3 JET DISCHARGES

5.3.1 General

For a jet discharge, the mixing phenomenon is dominated by the turbulence of the discharge and not the turbulence of the river. For non-buoyant effluents, the turbulence is achieved by high velocity nozzles designed to discharge effluent to a river.

There are many possible configurations for a jet discharge to a river, the most common are:

a) circular jets into a cross-flowing stream,
b) circular jets into a co-flowing stream,
c) plane (or line source) jets similar to a and b above.

In this report, the discussion is limited to circular jets in a crossflow because circular jets are easier to construct in pipe outfall systems and the mixing of crossflow jets is superior to the others. The general nature of both, side discharge jets and bottom discharge jets in a crossflow, has been described in Section 4.4.

For a jet discharge into a crossflow, the jet is deflected at an increasing rate until it is flowing parallel with the crossflow (Figure 6). The jet consists of three zones:

a) Potential Core Zone

This zone is also called the Zone of Flow Establishment. In the Potential Core Zone, the velocity of flow is very similar to the jet exit velocity. The jet axis experiences very little deflection in this zone. The extent of the Potential Core Zone for crossflow jets is in the order of 1 to 3 times the jet diameter.

b) Zone of Maximum Deflection

This is the zone of transition between the jet axis, which is perpendicular to the receiving stream velocity, to when the jet is parallel with the receiving stream velocity. In this zone, the jet is deformed from a circular shape to a kidney shape. This zone extends downstream for a distance of 20 to 25 times the jet diameter. This zone is most important when predicting the velocity and effluent concentration distributions.

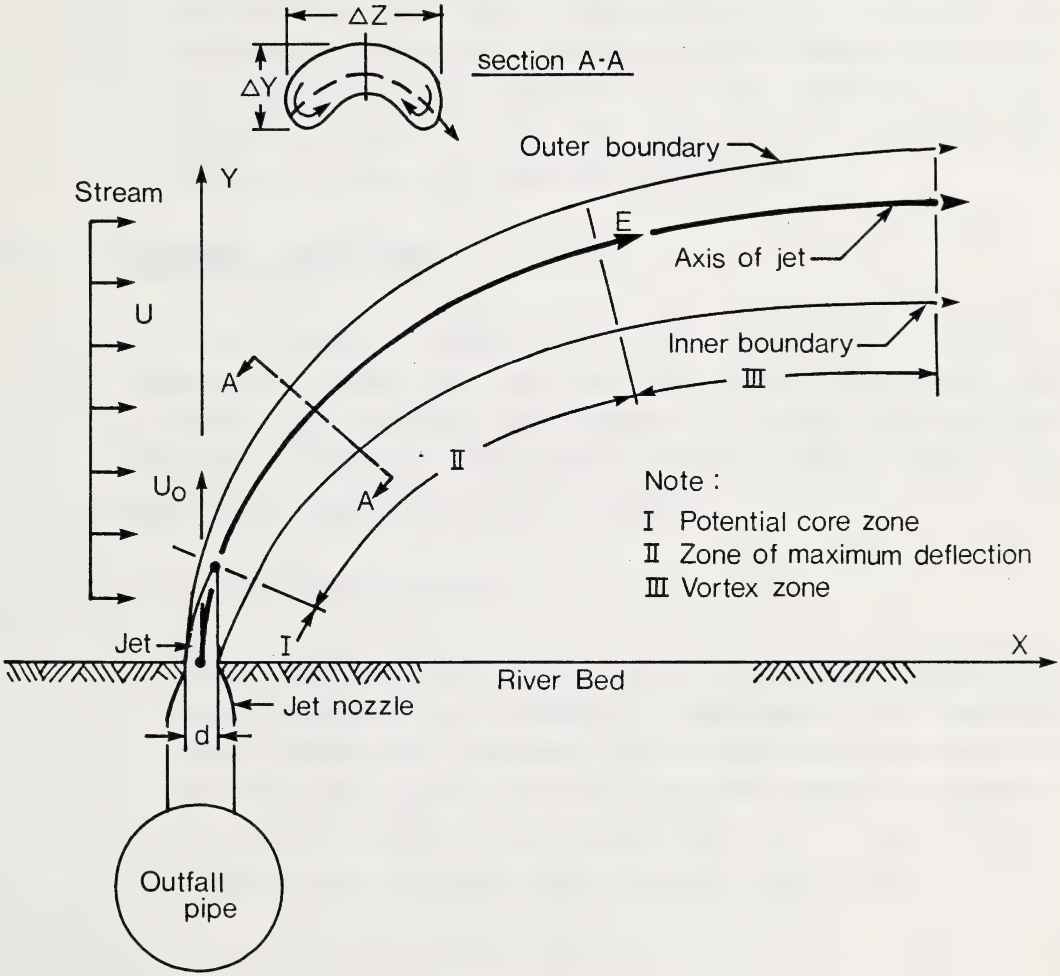

Figure 6. Bottom discharge jet in a crossflow.

c) Vortex Zone

In the vortex zone the jet direction and the jet velocities are approaching those of the receiving stream. Mixing in this zone is beginning to be influenced by the turbulence of the receiving stream. Within this zone, the jet maintains two distinct vortices as it progresses downstream.

5.3.2 Equations For Jet Flow

In this section, equations for the jet centreline location, boundaries, velocity, flow rate and the effluent concentration for a circular jet discharge are presented. These equations are embodied in computer model CRSJET which is used in Section 6 to illustrate the application of IDZ concepts.

a) Jet Centreline Equations

Many equations exist for predicting the centreline location of a jet discharging to a crossflow. Rajaratnam (1976) reported seven relationships developed from experimental observations. Of these, the equation of Pratte and Baines (1967) was based on the most extensive experimental data base. For a bottom discharge the centreline axis of the jet is given by:

$$y = 1.76 \cdot R \cdot d \cdot (X/R \cdot d)^{0.28} \tag{7}$$

where: y is the distance above the river bed (m),
R is the ratio of the jet velocity (Uo) to the river velocity (U),
d is the jet diameter (m), and
X is the distance downstream from the jet nozzle (m).

These experiments were conducted in a wind tunnel for values of R ranging from 5 to 35.

More recently, Rajaratnam and Gangadhariah (1980) conducted experiments in a water flume for jets with values of R ranging from 2.7 to 23. Their data fit the equation:

$$X = \frac{d \cdot Cd}{\pi R^2} (y/d)^2 \left(\frac{4y}{R \cdot d} + 1 \right) \tag{8}$$

where: Cd is the drag coefficient for the jet (assumed=1.5).

This equation requires an iterative solution when solving for y as a function of X (this is included in the program CRSJET).

b) Jet Boundaries

A jet in a crossflow has major and minor axes because of its kidney shape. Two equations are required to describe the width of the jet for each direction. Pratte and Baines (1967) found the jet width (DZ) in the major axis to be:

$$DZ = 1.45 \cdot d \cdot R \cdot [E/(d \cdot R)]^{0.33} \tag{9}$$

where: DZ is the jet width, in plan view for a bottom jet (m),
E is the distance along the jet axis (m).

The minor axis jet width is found to be:

$$DY = 1.11 \cdot d \cdot R \cdot [E/(d \cdot R)]^{0.33} \tag{10}$$

where: DY is the jet width, viewed from the side for a bottom jet (m).

The data from Rajaratnam and Gangadhariah (1980) are represented using the following equations:

$$DZ = 0.94 \cdot d \cdot (E/d + 1.3) \tag{11}$$

$$DY = 0.20 \cdot d \cdot (E/d + 3.5) \tag{12}$$

The results of these two sets of experiments differ appreciably; unfortunately, verification of either set of equations has not yet been made. However, it should be noted that width considerations are of slight importance in jet mixing because concentrations at the jet extremities are low.

c) Jet Velocities

The jet centreline velocity data from Rajaratnam and Gangadhariah (1980) can be expressed in the equation:

$$\frac{Um-U}{Uo-U} = \frac{1.82\ R^{0.69}}{(E/d)^{1.6}} \tag{13}$$

where: Um is the jet centreline velocity (m/s),
Uo is the jet exit velocity (m/s), and
U is the river velocity.

The distribution of velocity away from the centreline can be given by:

$$\frac{u - U}{Um - U} = \exp\left[-0.693\ (4 \cdot Z^1/DZ)^2\right] \tag{14}$$

where: u is the velocity at a point Z' away from the jet centreline (m/s),
Z' is the distance away from the jet centreline (m).

d) Jet Flow Rate

Equation (13) indicates a decrease in jet velocity as the jet progresses downstream. However, the jet flow rate increases due to the entrainment of the surrounding flow. Rajaratnam and Gangadhariah (1980) found that the flow rate at any section across the jet could be given by:

$$Q = 0.54 \cdot Qo\ (E/d)^{1.22} \tag{15}$$

where: Q is the jet flow rate at the section of interest (m^3/s),
Qo is the jet flow rate at the nozzle (m^3/s).

This equation can be rearranged to indicate the point where the dilution ratio (Q/Qo) is 20:1

$$E = 19\ d \tag{16}$$

This confirms that the Initial Dilution Zone is within the Zone of Maximum Deflection for a jet.

c) Jet Effluent Concentration

The average effluent concentration for the jet can be determined from the jet flow rates given by equation (15). The maximum concentration, which occurs very near the jet centreline, is approximately 1.4 times the average (Fischer et al. 1979).

5.3.3 Design Of Jet Discharges

To properly design a jet discharge it is important to choose the appropriate velocity, jet diameter, the number of jets and the jet spacing. These considerations are described in the following.

a) Jet Velocity (cavitation)

Cavitation in a flowing fluid is the local vaporization (i.e. 'boiling') of the fluid as it encounters a velocity discontinuity. Such a discontinuity exists at the outlet of a jet nozzle. Cavitation first manifests itself in the form of noise. If jet velocities are increased beyond the level where cavitation noise is first noticed, the cavitation can result in severe physical damage to the nozzles. For some effluents, any cavitation of the discharge is undesirable because it may cause foaming at levels where noise and physical damage does not occur.

Rouse (1953) found that cavitation occurs when the cavitation index (σ) is less than 0.6. Subsequent studies by Rouse (1966) indicated that physical damage can begin to occur when the cavitation index is less than 0.2. The equation for the cavitation index is:

$$\sigma = \frac{Po - Pv}{pUo^2/2} \tag{17}$$

where: Po is the ambient pressure at the jet nozzle (N/m^2), [Po = pgH]
Pv is the vapour pressure of the effluent (N/m^2),
p is the density of the fluid (Kg/m^3),
Uo is the jet exit velocity (m/s),
g is the acceleration due to gravity (9.81 m/s^2), and
H is the depth of water above the jet (m).

In jet design, if the more conservative value of 0.6 is used for the cavitation index, equation (17) can be rearranged to give an equation for the maximum allowable jet discharge velocity:

$$Uo < \sqrt{\frac{3.333\ (pgH-Pv)}{p}} \tag{18}$$

Values for the density and vapour pressure of water are presented in Appendix B. As an example, the application of equation (18) for a 20°C effluent discharge in 1.0 m of water gives a maximum allowable jet velocity of 4.3 m/s.

b) Jet Diameter

The jet diameter should be selected so that the effluent discharge does not bubble through the surface of the receiving stream. If it does, the mixing action will be poor. Using the equations of Pratte and Baines (1967) diameter constraint equations can be developed which will ensure adequate jet mixing. For bottom discharge jets:

$$d < \frac{H}{5.29 \quad R^{0.72}} \tag{19}$$

For side discharge jets, assuming the jet is discharged at mid-depth, the diameter constraint equation is:

$$d < \frac{H}{5.58 \quad R^{0.60}} \tag{20}$$

These equations typically give allowable jet diameters in the range of 0.050 m to 0.150 m in Alberta rivers.

c) Jet Flow Rate

After selecting a suitable jet configuration, the jet flow rate (Qj) is determined:

$$Qj = \frac{\pi \; d^2}{4} \quad Uo \tag{21}$$

There may be a need for multiple jets to discharge the total effluent flow.

d) Jet Spacing

The jet spacing should be such that the individual jets do not interfere with each other in the region up to the point where 20 to 1 dilution is achieved. The spacing can be based on the major axis width equations (9 and 11) for bottom discharge jets. It should be noted that it is usually easier to construct a bottom discharge outfall structure than a side discharge outfall structure when more than two jets are required.

e) Tracking the Jet

After the jet discharge has been designed its profile should be analyzed in detail. The program CRSJET has been developed to perform this analysis. The objective of the analysis is to achieve the required mixing (20 to 1 dilution on average) before the jet action subsides or is inhibited by the effects of the river bed, water surface or other jets.

In many cases jet mixing can reduce effluent concentrations to those of the receiving stream guidelines. If adequate dilution does not occur, smaller jets spaced over a wider outfall may be required. If jet mixing does not provide sufficient dilution, then a comprehensive two dimensional dispersion model, such as RIVMIX or TRSMIX, are required to simulate the discharge and evaluate the LUZ.

6.0 AN EXAMPLE FOR PREDICTING WATER QUALITY CHANGES

6.1 GENERAL

a) Effluent Conditions

The example illustrates the use of an IDZ for evaluating water quality changes in a receiving stream. This is accomplished by comparing water quality changes associated with point source discharges, line source discharge and jet discharge. Furthermore, the example provides an aid in using the equations and interpreting the results.

The example is based on a hypothetical CTMP mill located on the Athabasca River near Windfall, Alberta. The effluent characteristics are selected based on a mill capacity of 500 t/d.

Although there are several water quality parameters that may be of concern in a CTMP mill effluent, only one parameter is investigated in this example. It is assumed that abietic acid is the critical parameter in the effluent and controls the outfall design. The following characteristics have been assumed for the effluent discharge:

Effluent Flow Rate (QEFL)	0.145 m^3/s
Effluent Concentration - Abietic Acid (CEFL)	8.0 mg/L
Background Concentration - Abietic Acid (CB)	0.0 mg/L
Acute Toxicity Concentration - Abietic Acid	1.1 mg/L
Receiving Stream Guideline - Abietic Acid (CS)	0.04 mg/L
LUZ Boundary Width (pl)	0.4 (Maximum)

The winter flow condition is used to exemplify a worst case condition. In winter, the flow rate is the lowest and the mixing zone length is the longest.

b) Fully Diluted Effluent Concentration

The concentration of Abietic Acid at the end of the mixing zone:

$$CA = \frac{QEFL\ (CEFL) + QR\ (CB)}{QEFL + QR}$$

$$= \frac{0.145\ (8.0) + 32\ (0.0)}{0.145 + 32}$$

$$= 0.036\ mg/L$$

Because the effluent concentration (0.036 mg/L) is just below the receiving stream guideline (0.04 mg/L), the effluent discharge may be acceptable. However, because the completely mixed effluent concentration is only slightly less than the receiving stream guideline, knowledge of the concentrations within the mixing zone is required in order to assess possible impacts on water users.

6.2 POINT SOURCE DISCHARGE

a) Bank Outfall

For a bank outfall, the mixing zone length is:

$$Xm = \frac{0.4\ B^2\ U}{Ez} = \frac{0.4\ (129^2)0.44}{0.027} = 108{,}000\ m$$

The concentration at the critical point on the LUZ boundary is:

$$CL = CA/(2.066\ pl) = 0.036/(2.066 \cdot 0.4) = 0.044\ mg/L$$

The location of the critical point on the LUZ boundary is:

$$XL = \frac{(pl\ B)^2\ U}{2\ Ez} = \frac{(0.4 \cdot 129)^2\ 0.44}{2\ (0.027)} = 22{,}000\ m$$

The shoreline extent of the LUZ is approximated by:

$$Xsce = \left(\frac{CA}{CS}\right)^2 \frac{B^2\ U}{\pi\ Ez} = \left(\frac{0.036}{0.040}\right)^2 \frac{129^2\ (0.44)}{\pi\ (0.027)} = 70{,}000\ m$$

A more exact solution would give Xsce = 80,000 m.

The LUZ configuration for the bank outfall discharge condition is shown on Figure 7. If this configuration is unacceptable, other outfall configurations must be assessed (as shown below) or the effluent quality must be improved.

b) Midstream Outfall

A midstream outfall has a mixing zone length of about 1/4 that of a bank outfall (i.e. in this case, 27,000 m). Similarly, the location of the critical point for the LUZ (which occupies a width of pl = 0.2 on either side of midstream) is 1/4 that for a bank outfall (i.e. 5,550 m). The concentration at this point on the LUZ boundary is 0.044 mg/L.

Because the discharge is in midstream, no portion of the shoreline is occupied by the LUZ. The maximum longitudinal extent of the LUZ is about 20,000 m (1/4 that for the bank outfall).

By relocating the discharge point to midstream, the shoreline zone is avoided by the LUZ and the longitudinal extent of the LUZ is significantly reduced (Figure 7).

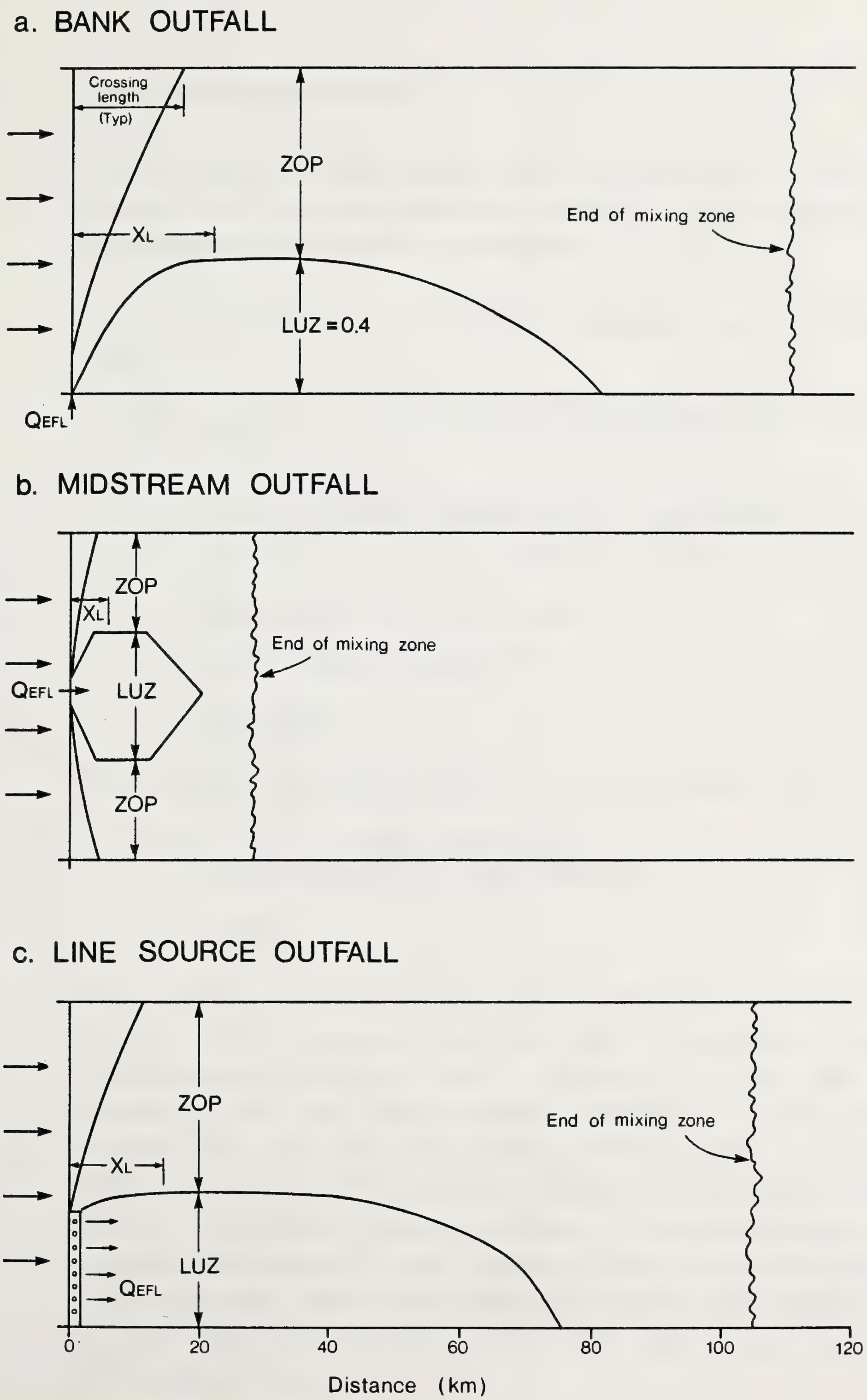

Figure 7. LUZ configuration for passive plume discharges.

6.3 LINE SOURCE DISCHARGE

A line source discharge should extend to a point that is less than the width of a maximum allowable LUZ width. In this case, a line source width (w) of 0.35 is investigated.

The maximum concentration on the LUZ boundary is given by equation (4):

$$CL = \frac{0.036}{2(0.35)} \left[\mathrm{erf}\left\{\frac{(0.4+0.35)\ [\ln(0.4+0.35) - \ln(0.4-0.35)]}{2\sqrt{0.4\ (0.35)}}\right\} - \mathrm{erf}\left\{\frac{(0.4-0.35)\ [\ln(0.4+0.35) - \ln(0.4-0.35)]}{2\sqrt{0.4\ (0.35)}}\right\} \right]$$

$$= 0.051\ [\mathrm{erf}(2.714) - \mathrm{erf}(0.181)]$$

$$= 0.051\ (0.9999 - 0.2018)$$

$$= 0.041 \text{ mg/L}$$

The location of the critical point is given by equation (5):

$$XL = \frac{0.4\ (0.35)\ 129^2\ (0.44)}{0.027\ [\ln(0.4+0.35) - \ln(0.4-0.35)]}$$

$$= 14{,}000 \text{ m}$$

The shoreline extent of the LUZ must be determined using equation (1) and making successive trials for Xsce. The solution for this discharge configuration is Xsce = 75,000 m. In this case, the benefit of the line source outfall is slight. A line source shortens the LUZ when the majority of the mixing zone is not required to reduce the instream effluent concentrations to the level of the receiving stream guideline. The reason is that this outfall configuration is most effective within the early part of the mixing zone. After some distance downstream, the turbulence of the river governs the extent of the LUZ rather than the outfall configuration (Figure 7).

6.4 JET DISCHARGE

If an IDZ with a 20 to 1 dilution is established, then the average concentration at the end of the IDZ is 0.4 mg/L. The maximum concentration is at the jet centreline and is about 40% greater than the average value, resulting in a concentration of 0.56 mg/L. Because this concentration is greater than the receiving stream guideline (i.e. CS = 0.04 mg/L), the IDZ does not establish adequate mixing by itself; the LUZ is larger than the IDZ. However, because a jet discharge can achieve 20:1 mixing within a few metres of the discharge ports, a jet discharge should still be considered because it minimizes the zone of acute toxicity (i.e. with concentrations greater than 1.1 mg/L), as shown on Figure 8.

Design of the jet discharge is outlined in the following:

a) Variables given:

QEFL = 0.145 m^3/s

CEFL = 8.0 mg/L

Tc = 5°C (winter); 15°C (fall)

QR = 32 m^3/s (winter); 110 m^3/s (fall)

CB = 0.0 mg/L

H = 0.95 m (winter); 1.38 m (fall)

U = 0.52 m/s (winter); 0.95 m/s (fall)

b) Jet Velocity:

The allowable jet velocity equation (18) is:

$$Uo < \sqrt{\frac{3.333\ (p\ g\ H - Pv)}{p}}$$

Selecting p and Pv from Appendix B for 5°C and 15°C gives maximum allowable velocities of 5.3 m/s for winter and 6.3 m/s for fall.

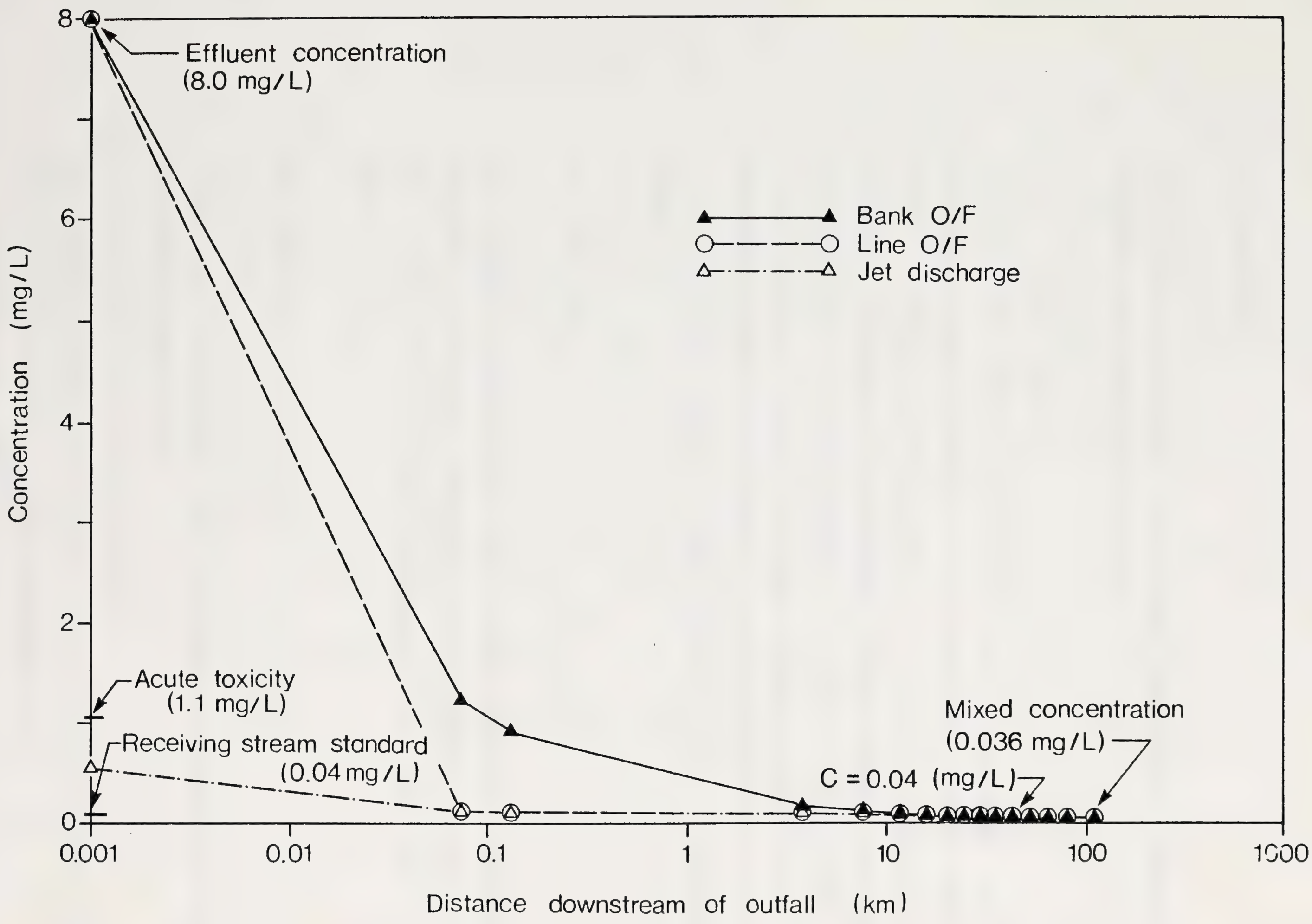

Figure 8. Comparison of discharge methods - right bank concentrations.

c) Jet Diameter:

For a bottom discharge, the maximum allowable jet diameter (d) is determined from equation (19):

$$d < \frac{H}{5.29 \cdot R^{0.72}}$$

Using a jet velocity of about 6.2 m/s to represent the fall discharge (which gives R = 6.4) and about 3.1 m/s for the winter discharge (which gives R = 6.0), the maximum jet diameters determined from equation (18) are 0.068 m and 0.050, respectively. In this example a 0.0635 m (2-1/2 inch) jet nozzle diameter is used. One row of jets is used for the fall discharge (with a high velocity) and two rows of jets for the winter discharge (more jets are needed to mix in the shallow flow).

d) Jet Flow Rate:

With 0.0635 m diameter jets and the jet velocities indicated in c) above, 15 jets are needed for the fall discharge and 30 jets are needed for the winter discharge (i.e. two rows of 15 jets).

e) Jet Spacing:

Pratte and Baines (1967) width expression (equation 9) is used for the jet spacing (Z):

$$Z = 1.45 \cdot d \cdot R\ (E/d \cdot R)^{0.33}$$

As indicated earlier the 20 to 1 mixing is accomplished before E/d = 20, this equation can be simplified to:

$$Z = 3.90 \cdot d \cdot R^{0.67}$$

For the winter discharge (R = 6.0), this results in a minimum required spacing of 0.82 m. The jet spacing could occupy a width as small as 0.82 (30-1) = 23.8 m. This spacing requires that the river flow rate be about 23.8 (0.95) 0.52 = 11.7 m^3/s or about 35% of the river.

f) Tracking the Jet:

The program CRSJET can be used to confirm that the proposed jet configuration is acceptable. The winter and fall discharge conditions are simulated to show that the jet profile is acceptable (see Appendix C).

In examining the output from the program CRSJET in Appendix C, note that several tables of information are presented:

- the input and computed system variables,
- the centreline profiles by seven different methods,
- the jet conditions based on the work of Pratte and Baines,
- the jet conditions based on the work of Rajaratnam, Gangadhariah and Hodgson, and
- a longitudinal plot of the jet.

In Appendix C, the plots are based on the work of Rajaratnam, Gangadhariah and Hodgson. Their work is more applicable because the experiments are based on a water flume as opposed to those in air.

7.0 CONCLUSIONS

The IDZ can be used to reduce possible impacts of effluents discharged to receiving streams as described by the following.

7.1 BENEFITS

Although, the implementation of an IDZ requires additional design and construction costs related to the outfall pipe and jet nozzles, in some cases the benefits may be worth the expenditure. The benefits that could be achieved by establishing an IDZ include:

a) In cases where 20:1 dilution can reduce the effluent concentration to below that of the receiving stream guideline, the jet discharge limits the extent of the LUZ to the IDZ (i.e. within a few metres of the outfall).

b) By establishing an IDZ, there is less dependance on the turbulence of the river for mixing. The jet turbulence, being in the control of the designer, is more significant and more dependable. This is of value even if 20:1 dilution is not sufficient to allow receiving stream guidelines to be met.

c) In cases where toxic effluents are being discharged, the 20:1 dilution can reduce or eliminate the zone of acute toxicity. Although the LUZ concept allows concentrations to be higher than the receiving stream guidelines, it is highly desirable that zones of acute toxity be eliminated.

7.2 LIMITATIONS

There are a number of limitations to using jets and establishing an IDZ in a receiving stream. These have been explained within the foregoing and are summarized in the following:

a) The maximum jet velocity should be controlled to prevent problems associated with cavitation (foaming, noise, damage to piping). Equation (18) has been developed to determine the limiting jet velocity. Typical values for Alberta rivers would be in the order of 5 m/s.

b) The maximum jet diameter is depth dependent. Equations (19) and (20) have been developed to determine the maximum jet diameter. Typical values for Alberta rivers would be in the order of 0.050 m to 0.150 m.

c) Jets must be spaced adequately to prevent their interference. Equations (9) and (11) have been developed to determine the jet spacing for bottom discharge jets. Typical values for Alberta rivers would be in the order of 1.0 m.

d) Jet mixing can only be relied upon in the Zone of Maximum Deflection. This zone extends downstream for a distance of about 25 times the jet diameter. Mixing of at least 20:1 can be accomplished in this zone. If dilutions of greater than 20:1 are required, mixing in the receiving stream due to river turbulence must be considered.

7.3 IDZ FOR PROTECTING RECEIVING STREAMS IN ALBERTA

There are several instances where the establishment of an IDZ would be appropriate for the protection of Alberta's receiving streams. These include:

a) In case of high strength effluents (containing highly toxic contaminants).

b) Where effluents have densities different from that of the receiving stream which may inhibit mixing.

c) In deep river reaches where vertical mixing may be slow.

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APPENDIX A

VALUES FOR THE ERROR FUNCTION

Appendix A. Values for the error function.

X	erf (X)	X	erf (X)
0.0	0.0	1.0	0.8427
0.1	0.1129	1.2	0.9103
0.2	0.2227	1.4	0.9523
0.3	0.3286	1.6	0.9763
0.4	0.4284	1.8	0.9891
0.5	0.5205	2.0	0.9953
0.6	0.6309	2.5	0.9996
0.7	0.6778	3.0	0.99998
0.8	0.7421	4.0	1.0000
0.9	0.7969	∞	1.0000

Note: Taken from Fischer et al. (1979).

APPENDIX B

SELECTED PROPERTIES OF WATER

Appendix B. Selected properties of water.

Temp (°C)	Density (Kg/m^3)	Vapour Pressure (N/m^2)
0	999.8	610
5	1000.0	870
10	999.7	1230
15	999.1	1700
20	998.2	2340
25	997.0	3170
30	995.7	4240

APPENDIX C

OUTPUT FROM PROGRAM CRSJET

<1> TITLE LINE 1: ATHABASCA RIVER -- ABIETIC   ACID
<2> TITLE LINE 2: WINTER (32 m3/s) -- Uo = 3.1 m/s
<3> UNITS (0 = metric; 1 = english)........... 0
<4> DEPTH (m or ft)......................... 0.95
<5> WIDTH (m or ft)........................ 12.00
<6> VELOCITY (m/s or fps).................. 0.520

*** JET DATA ***

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<2> VELOCITY (m/s or fps)............... 3.100
<3> DOWNSTREAM STATIONING (X/D min)..... 2
<4> DOWNSTREAM STATIONING (X/D max)..... 20
<5> STATIONING INCREMENT (X/D units).... 1
<6> JET TYPE (1 = side; 2 = bottom)..... 2

*** COMPUTED VALUES ***

VELOCITY RATIO (alpha)............... 5.96
RIVER FLOW RATE (m3/s or cfs)...... 5.928
JET FLOW RATE (m3/s or cfs)........ 0.010

HIT ANY KEY TO CONTINUE.....

*** CRSJET -- JET IN A CROSSFLOW -- VERSION 1.0 ***

2	0.127	0.355	0.491	0.377	0.341	0.403	0.367
4	0.254	0.455	0.596	0.474	0.447	0.521	0.464
6	0.381	0.525	0.667	0.542	0.523	0.605	0.533
8	0.508	0.580	0.723	0.596	0.585	0.673	0.587
10	0.635	0.627	0.770	0.642	0.639	0.731	0.634
12	0.762	0.668	0.810	0.681	0.686	0.782	0.674
14	0.889	0.705	0.846	0.717	0.728	0.828	0.710
16	1.016	0.739	0.878	0.749	0.767	0.870	0.743
18	1.143	0.769	0.908	0.779	0.803	0.908	0.774
20	1.270	0.798	0.935	0.807	0.837	0.944	0.802
22	1.397	0.825	0.960	0.832	0.869	0.978	0.828
24	1.524	0.850	0.984	0.857	0.899	1.010	0.853
26	1.651	0.873	1.006	0.880	0.927	1.041	0.877
28	1.778	0.896	1.027	0.901	0.954	1.070	0.899
30	1.905	0.918	1.047	0.922	0.980	1.097	0.921

HIT ANY KEY TO CONTINUE.....

*** EQUATIONS FROM WORK OF PRATTE & BAINES ***

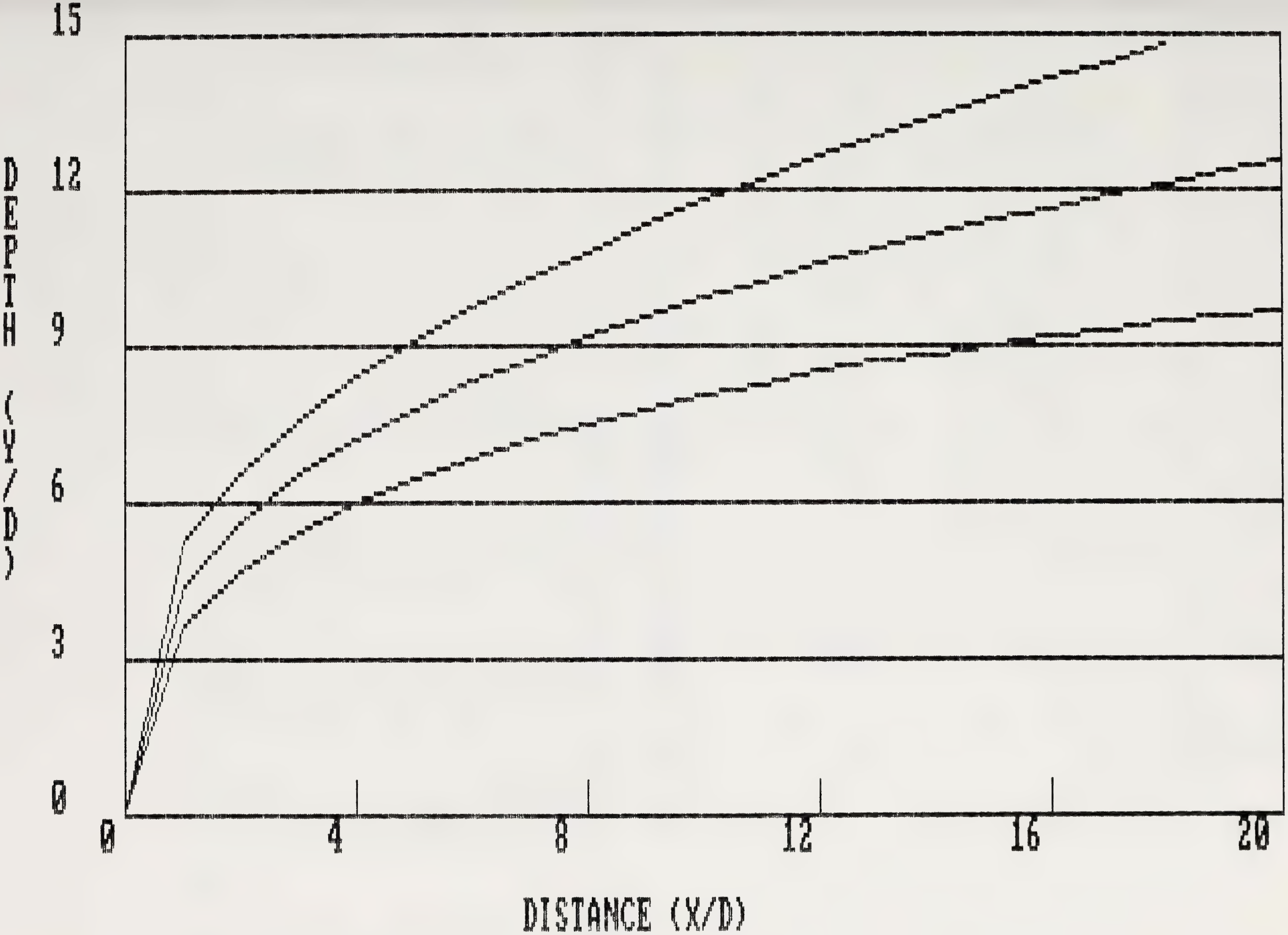
X/D	X	Yc	E	E/D	PLUME WIDTHS		Um	Um/Ur	Q/Qo
2	0.13	0.49	0.52	8.13	0.61	0.47	1.10	2.11	6.97
4	0.25	0.60	0.68	10.73	0.67	0.51	0.86	1.64	9.77
6	0.38	0.67	0.83	13.03	0.72	0.55	0.74	1.42	12.38
8	0.51	0.72	0.97	15.22	0.75	0.58	0.67	1.29	14.96
10	0.63	0.77	1.10	17.35	0.79	0.60	0.63	1.20	17.55
12	0.76	0.81	1.23	19.45	0.82	0.63	0.60	1.15	20.17
14	0.89	0.85	1.37	21.52	0.85	0.65	0.58	1.11	22.83
16	1.02	0.88	1.50	23.59	0.87	0.67	0.56	1.08	25.53
18	1.14	0.91	1.63	25.64	0.90	0.69	0.55	1.06	28.27
20	1.27	0.94	1.76	27.69	0.92	0.70	0.55	1.05	31.04
22	1.40	0.96	1.89	29.73	0.94	0.72	0.54	1.04	33.85
24	1.52	0.98	2.02	31.76	0.96	0.74	0.54	1.03	36.70
26	1.65	1.01	2.15	33.79	0.98	0.75	0.53	1.03	39.59
28	1.78	1.03	2.27	35.82	1.00	0.77	0.53	1.02	42.50
30	1.91	1.05	2.40	37.84	1.02	0.78	0.53	1.02	45.45

HIT SELECTION: <1> main menu: or <2> plot.....

*** FROM WORK OF RAJARATNAM, GANGADHARIAH & HODGSON ***

X/D	X	Yc	E	E/D	PLUME WIDTHS		Um	Um/Ur	Q/Qo
2	0.13	0.36	0.38	6.06	0.44	0.12	1.45	2.80	4.87
4	0.25	0.45	0.55	8.61	0.59	0.15	1.04	2.00	7.46
6	0.38	0.52	0.69	10.89	0.73	0.18	0.85	1.63	9.94
8	0.51	0.58	0.83	13.07	0.86	0.21	0.74	1.41	12.43
10	0.63	0.63	0.97	15.21	0.99	0.24	0.67	1.29	14.97
12	0.76	0.67	1.10	17.31	1.11	0.26	0.63	1.20	17.55
14	0.89	0.71	1.23	19.39	1.24	0.29	0.60	1.15	20.10
16	1.02	0.74	1.36	21.46	1.36	0.32	0.58	1.11	22.75
18	1.14	0.77	1.49	23.52	1.48	0.34	0.56	1.08	25.44
20	1.27	0.80	1.62	25.57	1.60	0.37	0.55	1.07	28.17
22	1.40	0.82	1.75	27.61	1.73	0.40	0.55	1.05	30.94
24	1.52	0.85	1.88	29.65	1.85	0.42	0.54	1.04	33.75
26	1.65	0.87	2.01	31.68	1.97	0.45	0.54	1.03	36.59
28	1.78	0.90	2.14	33.72	2.09	0.47	0.53	1.03	39.48
30	1.91	0.92	2.27	35.74	2.21	0.50	0.53	1.02	42.39

HIT SELECTION: <1> main menu: or <2> plot.....


DEPTH (Y/D)
15
12
9
6
3
0
0
4
8
12
16
20
DISTANCE (X/D)

<1> TITLE LINE 1: ATHABASCA RIVER -- ABIETIC ACID
<2> TITLE LINE 2: FALL (110 m3/s) -- Uo = 6.2 m/s
<3> UNITS (0 = metric: 1 = english)........... 0
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<6> VELOCITY (m/s or fps).................. 0.950

*** JET DATA ***

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<2> VELOCITY (m/s or fps)................. 6.200
<3> DOWNSTREAM STATIONING (X/D min)...... 2
<4> DOWNSTREAM STATIONING (X/D max)...... 30
<5> STATIONING INCREMENT (X/D units).... 2
<6> JET TYPE (1 = side: 2 = bottom)..... 2

*** COMPUTED VALUES ***

VELOCITY RATIO (alpha)............... 6.53
RIVER FLOW RATE (m3/s or cfs)....... 15.732
JET FLOW RATE (m3/s or cfs)......... 0.020

HIT ANY KEY TO CONTINUE.....

*** CRSJET -- JET IN A CROSSFLOW -- VERSION 1.0 ***
*** COPYRIGHT (c) HODGSON ENTERPRISES NOVEMBER 1986 ***

2	0.127	0.389	0.524	0.408	0.366	0.431	0.396
4	0.254	0.498	0.636	0.513	0.480	0.557	0.501
6	0.381	0.574	0.712	0.587	0.562	0.647	0.575
8	0.508	0.635	0.772	0.645	0.629	0.720	0.634
10	0.635	0.687	0.822	0.694	0.686	0.781	0.684
12	0.762	0.732	0.865	0.737	0.737	0.836	0.728
14	0.889	0.772	0.903	0.776	0.782	0.885	0.767
16	1.016	0.809	0.938	0.811	0.824	0.930	0.803
18	1.143	0.842	0.969	0.843	0.863	0.971	0.836
20	1.270	0.873	0.998	0.873	0.899	1.010	0.866
22	1.397	0.903	1.025	0.901	0.933	1.046	0.895
24	1.524	0.930	1.050	0.927	0.965	1.080	0.922
26	1.651	0.956	1.074	0.952	0.996	1.113	0.947
28	1.778	0.981	1.097	0.975	1.025	1.144	0.971
30	1.905	1.005	1.118	0.998	1.053	1.173	0.994

HIT ANY KEY TO CONTINUE.....

*** EQUATIONS FROM WORK OF PRATTE & BAINES ***

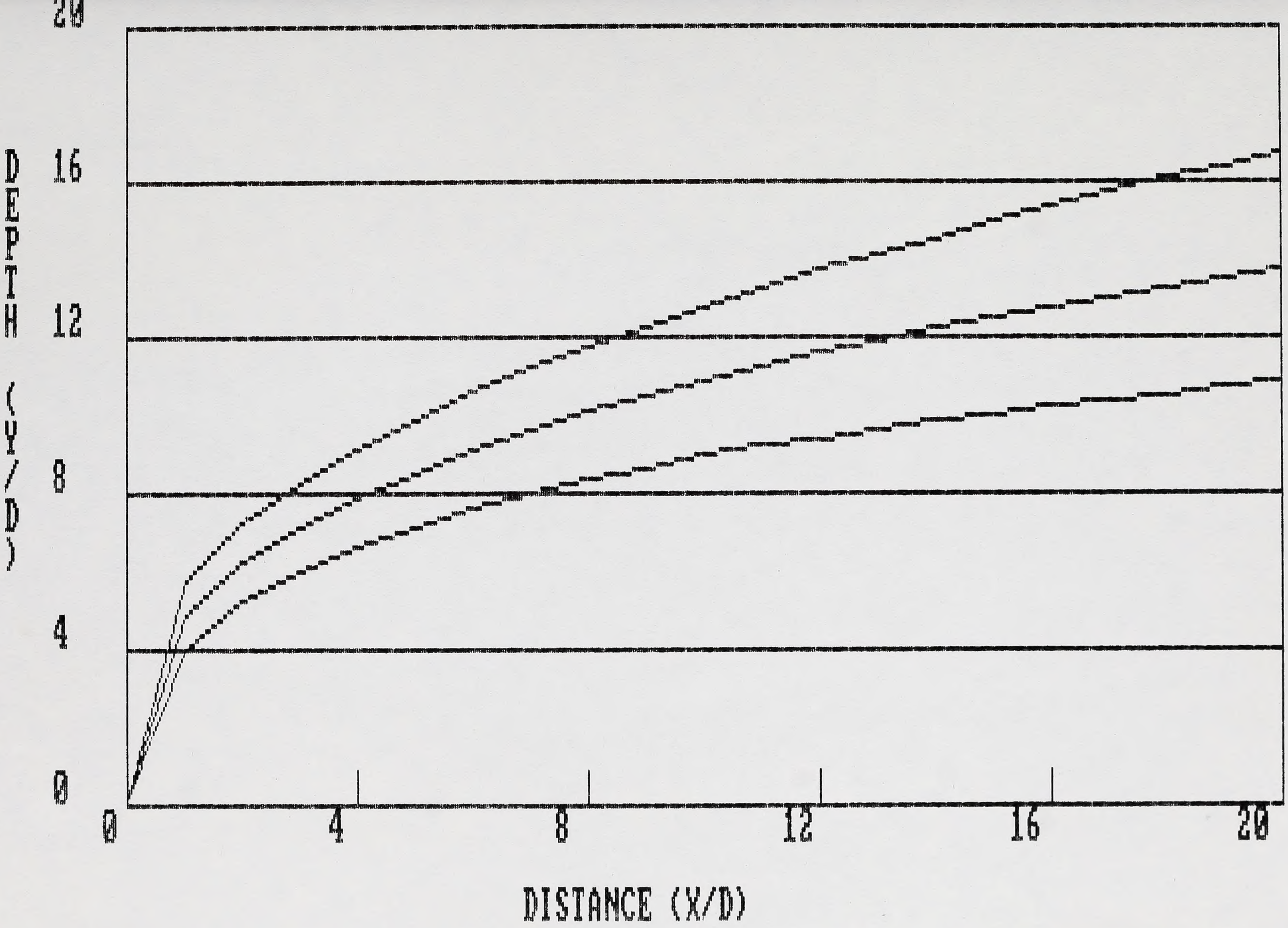
X/D	X (m)	Yc (m)	E (m)	E/D	PLUME WIDTHS max	PLUME WIDTHS min	Um (m/s)	Um/Ur	Q/Qo
2	0.13	0.52	0.55	8.63	0.66	0.51	2.08	2.19	7.49
4	0.25	0.64	0.72	11.31	0.73	0.56	1.61	1.70	10.41
6	0.38	0.71	0.87	13.64	0.77	0.59	1.38	1.46	13.09
8	0.51	0.77	1.01	15.85	0.81	0.62	1.25	1.32	15.72
10	0.63	0.82	1.14	18.00	0.85	0.65	1.17	1.23	18.36
12	0.76	0.87	1.28	20.11	0.88	0.67	1.11	1.17	21.02
14	0.89	0.90	1.41	22.20	0.91	0.70	1.07	1.13	23.71
16	1.02	0.94	1.54	24.27	0.94	0.72	1.04	1.10	26.44
18	1.14	0.97	1.67	26.33	0.96	0.74	1.02	1.08	29.20
20	1.27	1.00	1.80	28.38	0.99	0.75	1.01	1.06	32.00
22	1.40	1.03	1.93	30.43	1.01	0.77	0.99	1.05	34.83
24	1.52	1.05	2.06	32.47	1.03	0.79	0.99	1.04	37.70
26	1.65	1.07	2.19	34.50	1.05	0.81	0.98	1.03	40.61
28	1.78	1.10	2.32	36.53	1.07	0.82	0.97	1.03	43.54
30	1.91	1.12	2.45	38.56	1.09	0.84	0.97	1.02	46.51

HIT SELECTION: <1> main menu: or <2> plot.....

*** FROM WORK OF RAJARATNAM. GANGADHARIAH & HODGSON ***

X/D	X (m)	Yc (m)	E (m)	E/D	PLUME WIDTHS max	PLUME WIDTHS min	Um (m/s)	Um/Ur	Q/Qo
2	0.13	0.39	0.42	6.56	0.47	0.13	2.74	2.88	5.36
4	0.25	0.50	0.58	9.20	0.63	0.16	1.95	2.06	8.09
6	0.38	0.57	0.73	11.53	0.77	0.19	1.59	1.67	10.66
8	0.51	0.64	0.87	13.75	0.90	0.22	1.38	1.45	13.22
10	0.63	0.69	1.01	15.91	1.03	0.25	1.25	1.31	15.79
12	0.76	0.73	1.14	18.03	1.15	0.27	1.16	1.23	18.40
14	0.89	0.77	1.28	20.13	1.28	0.30	1.11	1.17	21.04
16	1.02	0.81	1.41	22.21	1.40	0.33	1.07	1.13	23.72
18	1.14	0.84	1.54	24.28	1.53	0.35	1.04	1.10	26.45
20	1.27	0.87	1.67	26.34	1.65	0.38	1.02	1.08	29.21
22	1.40	0.90	1.80	28.39	1.77	0.41	1.01	1.06	32.01
24	1.52	0.93	1.93	30.44	1.89	0.43	0.99	1.05	34.85
26	1.65	0.96	2.06	32.48	2.02	0.46	0.99	1.04	37.72
28	1.78	0.98	2.19	34.52	2.14	0.48	0.98	1.03	40.63
30	1.91	1.00	2.32	36.55	2.26	0.51	0.97	1.03	43.56

HIT SELECTION: <1> main menu: or <2> plot.....



DEPTH (Y/D)
0
4
8
12
16
20
0
4
8
12
16
20
DISTANCE (X/D)